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The Satellite-substructure Connection

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Abstract. We describe our recent attempts to model substructure in dark matter halos down to very small masses, using a semi-analytic model of halo formation. The results suggest that numerical simulations of halo formation may still be missing substructure in the central regions of halos due to purely numerical effects. If confirmed, this central 'overmerging' problem will have important consequences for the interpretation of lensing measurements of substructure. We also show that the spatial distribution of subhalos relative to the satellite companions of the Milky Way rules out at least one simple model of how dwarf galaxies form in low-mass halos.

1. Introduction

When numerical simulations of cold dark matter (CDM) halo formation reached sufficient resolution a few years ago, they revealed that a wealth of dense substructure, the undigested remains of ancient hierarchical merging, should still survive in these systems at the present day (Klypin et al. 1999; Okamoto & Habe 1999; Moore et al. 1999). The properties of halo substructure will be a sensitive test of the nature of dark matter if we can manage to quantify them observationally, for instance in strong gravitational lens systems (cf. talks by P. Schneider and N. Dalal in these proceedings). Halo substructure must also be linked to satellite galaxies, such as the dozen dwarf satellites of the Milky Way, although the exact nature of the connection remains problematic, given the huge discrepancy between the number of subhalos predicted by simulations and the number of luminous satellites observed locally.

Before we can reach firm conclusions on the properties of halo substructure or the nature of the satellite-substructure connection, however, we should first confirm that current simulations of substructure have converged to a definite and accurate prediction of its properties. For many years, N-body simulations suffered from 'overmerging', the artificial disruption of substructure due to numerical effects. It is still not clear that all the properties of simulated halo substructure have converged to level required for applications such as lens modeling. To test for the possibly of residual overmerging, we will compare purely numerical results with semi-analytic (SA) predictions, using a recently developed SA model of halo formation.

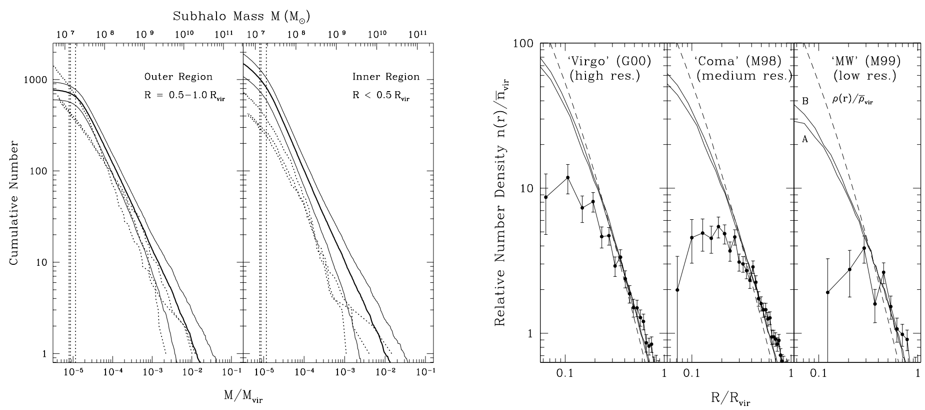

Figure 1. a: (*left*) Subhalo mass functions from simulations and from the SA model of TB03 (dotted and solid lines respectively). b: (*right*) The relative number density of subhalos in three different simulations (lines with error bars), compared with the SA model (solid lines), and the background density profile (dashed line).

2. Is Overmerging Over Yet?

The SA model of Taylor & Babul (2003, TB03 hereafter) provides an alternative to direct numerical simulation of halo formation. It combines extended Press-Schechter merger histories, which predict when subhalos merge, with an analytic description of orbital evolution and mass loss, which determines how they evolve subsequently. While the model is approximate in many ways, it also avoids some of the strongest biases in the purely numerical studies, and thus provides an interesting point of comparison.

Fig. 1a shows the mass spectrum of subhalos in simulations by Moore et al. (1998, 1999) and Ghigna et al. (2000) (dotted lines), compared with the SA model of TB03 (thick solid lines, with thin solid lines showing the 1-σ variance). In the outer part of the halo, the two techniques agree to within 10–20%. In the inner regions, where higher densities and longer evolution times would enhance numerical overmerging, the SA model predicts up to twice as much substructure at a given mass. In Fig. 1b, we compare the spatial distribution of subhalos in simulations of increasing resolution (panels from right to left). While the amount of central substructure increases slowly with resolution, there is no obvious sign of convergence – simulations at even higher resolution might find yet more subhalos in the central regions, as predicted by the SA model (solid lines).

3. Implications for Lensing Measurements of Substructure

By examining flux-ratio anomalies in multiply imaged quasars, strong lensing studies can constrain the amount of substructure along lines of sight through the center of galactic halos. Robust predictions of the amount of central sub-

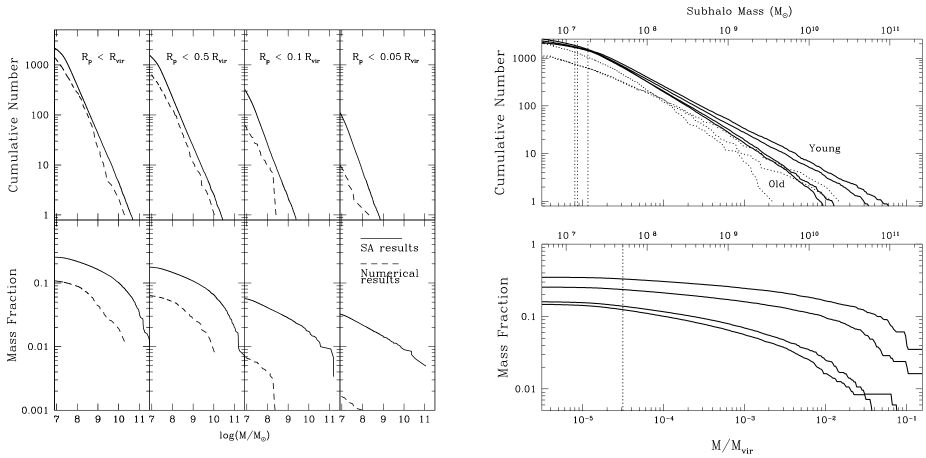

Figure 2. a: (*left*) The cumulative mass functions (top panels) and cumulative mass fraction in substructure (bottom panels) in the highest resolution simulation (Ghigna et al. 2000; dashed lines), compared with the average in the SA model (solid lines). b: (*right*) The cumulative mass function and cumulative mass fraction for four sets of SA trees of increasing dynamical age.

structure are essential to take full advantage of this work. Fig. 2a compares predictions for the number of subhalos and the mass fraction in substructure in the highest-resolution simulation and in the SA model. The differences discussed previously produce an order-of-magnitude increase in the predicted mass fraction in the central regions. Interestingly, the level predicted by the SA model is roughly that inferred from observations (e.g. N. Dalal, these proceedings). The SA model also predicts a large scatter in the mass fraction, however. Fig. 2b shows that the amount of substructure decreases as systems age. Dynamically young systems (those whose halos have formed recently) have 3–4 times more mass in substructure then more relaxed systems. This large scatter implies that sample selection will be an important factor in lensing studies.

4. The Satellite-substructure Connection

Many explanations have been proposed to account for the apparent discrepancy between the large numbers of subhalos predicted in CDM models and the few luminous satellites seen around galaxies like the Milky Way. Two generic solutions are that early photoionization heated gas in low-mass halos, halting star formation in all but the oldest of these systems (e.g. Bullock et al. 2000; Benson et al. 2002), or alternatively that strong feedback suppresses star formation in all low-mass halos, and that observed dwarf galaxies actually reside in the central parts of much larger CDM subhalos (Stoehr et al. 2003, Hayashi et al. 2003). To distinguish between these models, we can ask more generally: are local satellites associated with the most massive subhalos, or with the oldest subhalos? Fig. 3 shows the cumulative radial distribution of satellites around the Milky Way, (assuming a virial radius of 310 kpc) compared with the average

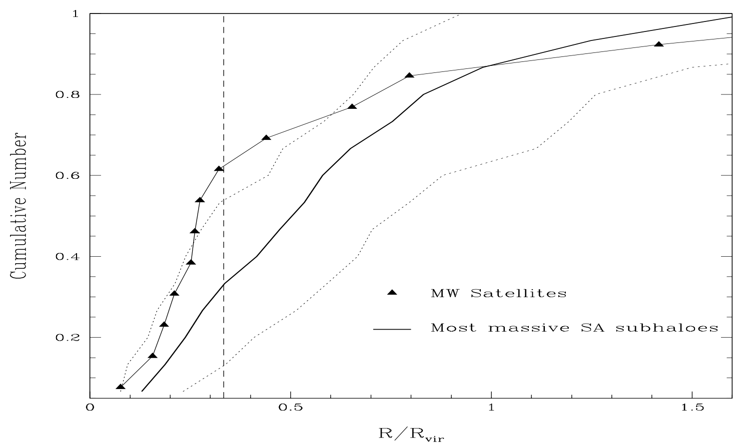

Figure 3. The cumulative radial distribution of Milky Way satellites (triangles), compared with the average for the dozen most massive systems in a large set of SA halos (solid line, with the dashed lines indicating the 10% and 90% contours of the distribution).

distribution of the dozen most massive subhalos found in each of several hundred merger trees. The satellites are clearly more clustered than the most massive subhalos. Two-thirds of them are within roughly 100 kpc of the Milky Way, for instance, whereas fewer than 1 tree in 100 shows this degree of clustering for its most massive substructure. More detailed analysis (Taylor, Babul & Silk, in preparation) strengthens the conclusion that the luminous satellites of the Milky Way must correspond to the oldest substructures in its halo, rather than the most massive ones.

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